COMMUNICATIONS UNDERWATER

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This invited contribution is intended for an audience familiar with general underwater acoustics but which wishes to gain more understanding of underwater communication using acoustic waves as a carrier. We will review some basic concepts applicable to any communication system as well as some of the diverse concepts and experimental and commercial systems used for communicating underwater.

Topics considered include: acoustic transducers and arrays, some applications of underwater acoustic communications, analogue modulations, multipath, noncoherent and coherent digital transmission schemes including phase modulation, channel equalization, and state of the art. Extensive literature on the subject is provided.

INTRODUCTION

The demand for underwater communications (including telemetry and control) is driven by a number of needs, such as:

- Free swimming diver-to-diver or diver-to-ship voice communications;
- Submarine-to-submarine or submarine-to-surface platform communications;
- Control and monitoring of offshore oil/gas drilling/production platforms or other bottom installations;
- Control and monitoring of Autonomous Underwater Vehicles (AUV);
- Monitoring of marine wildlife;
- Monitoring of fishing nets;

- Transmission of data accumulated by moving or stationary underwater platforms, including still photography, video, sonar and other broadband signals;
- Surveillance of certain water bodies for security and environmental monitoring.

The prime reason for using an acoustic carrier for short range (up to several kilometers), high rate communications (up to several kbytes/s) is the low absorption of acoustic energy by sea water in comparison to that of electromagnetic energy. For instance, energy absorption at f = 10 kHz is 3000 dB/km for electromagnetic waves and only 1 dB/km for sonic waves. Thus, using an acoustic carrier is considerably more energy-efficient than the use of electromagnetic radiation.

The main obstacle to a high data transmission rate in an acoustic channel is the presence of a strong multipath originating from multiple reflections between bottom and surface boundaries. Table 1 provides a comparison between an electromagnetic communication system and an underwater acoustic system. The duration of an acoustic multipath, measured in terms of transmitted symbols, is remarkably longer than that of a typical land mobile electromagnetic communication system. We also note very few carrier cycles within a symbol duration for an acoustic system compared to an electromagnetic system.

Tab. 1. Comparisons between land mobile and underwater communication systems

Parameters	**Land Mobile**	**Underwater**
Carrier frequency	1 GHz	10 kHz
Wavelength	3 cm	15 cm
Channel Bandwidth	30 kHz	2 kHz
Signaling rate	24 ksymbols/s	2 ksymbols/s
Symbol duration	42 μs	500 μs
Carrier cycles/symbol	4.2×10^4	5
Platform speed	100 km/h (car)	18 km/h (submersible)
Carrier Doppler shift	9.3×10^{-4} %	3.33×10^{-3} %
Multipath time spread	10 ms	50-100 ms
Symbols in that time	0.24	100-2000

1. ACOUSTIC TRANSDUCERS AND ARRAYS

An acoustic transducer is a device for converting electrical energy into acoustic energy. A typical transducer can be represented as a resonant circuit (band-pass filter, BPF) with the following parameters:

- a central frequency, f;
- a bandwidth, B;
- a resultant Q factor, f/B;
- a wavelength = sound velocity/f; and
- physical dimensions, n, measured in terms of n = wavelength/dimension.

As an illustration, consider a narrowband channel centered at a carrier frequency of f = 50 kHz and bandwidth of B = 10 kHz. We can represent such a channel by a 5th-order Butterworth BPF with Q = 5. The impulse response of such a filter is shown in Figure 1. We note that the product of the response duration T_p and the filter bandwidth B is equal to approximately 1.2

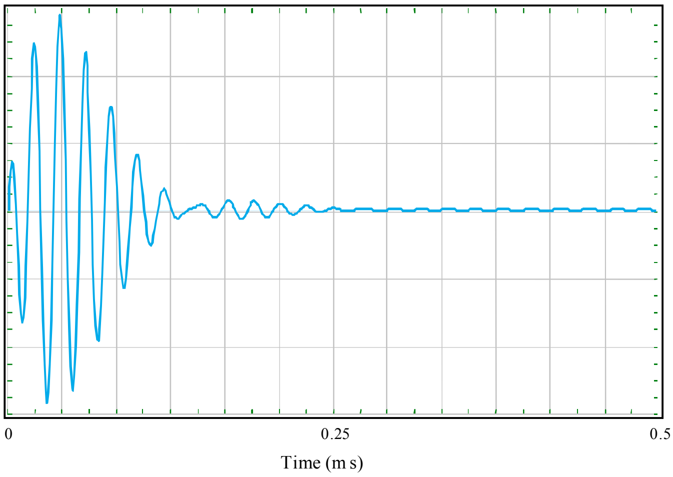


Fig. 1. Impulse response of an acoustic transducer

The radiation pattern of an acoustic transducer (or transducer array) depends on its geometry and size. Radiation patterns for a linear traducer and piston transducer are shown in Figure 2 and Figure 3, respectively.

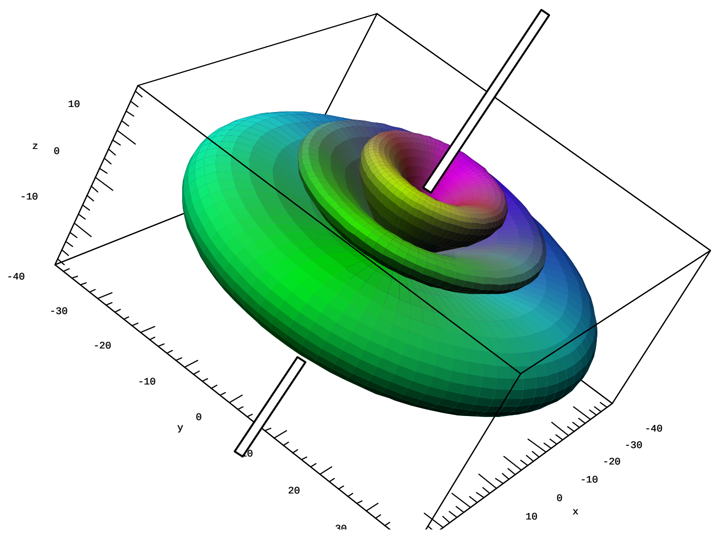


Fig. 2. Radiation pattern of a line transducer

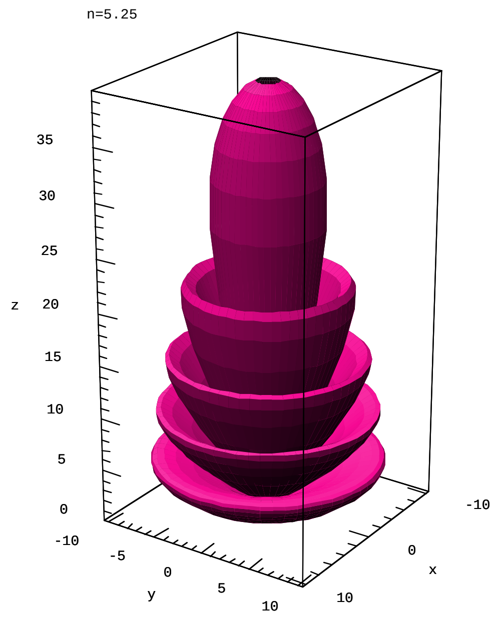


Fig. 3. Radiation pattern of a piston transducer

In both patterns we observe the existence of sidelobes that are generally an undesirable property for a variety of reasons.

2. APPLICATION - TSUNAMI WARNING SYSTEM

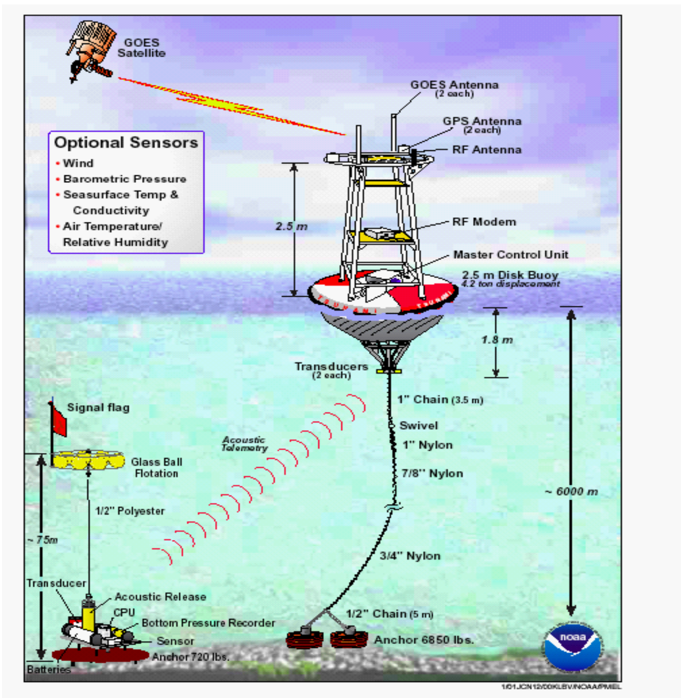


Fig. 4. Tsunami Warning System

An example of an application of an underwater acoustical system is the open ocean tsunami warning system shown in Figure 4. The slight increase of hydrostatic pressure caused by a tsunami surface wave is detected by a bottom pressure sensor; this information is transmitted over an acoustic link to a surface buoy. From there the warning is transmitted in almost real time by a satellite to the Tsunami Warning Center.

3. THE ACOUSTIC CHANNEL

The near vertical acoustic link from fixed platforms such as that used for tsunami detection is of relatively good quality. In other cases, however, particularly in shallow water and a near horizontal link, the acoustic channel is severely limited by multipath with time and frequency spread. The duration and intensity of multipath can be assessed by transmitting a very narrow high frequency pulse and observing the envelope of the signal received at a certain location. A sample of such a response is presented in Figure 5.

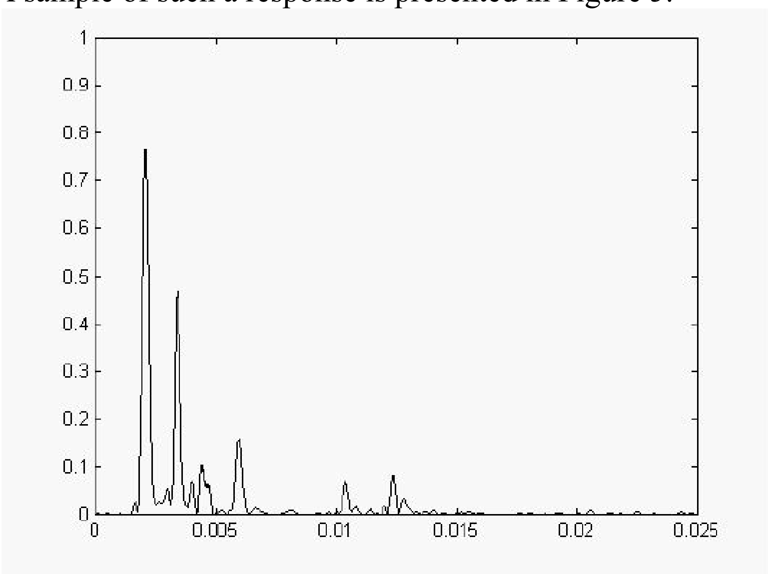


Fig. 5. Envelope of the response to a narrow pulse transmission

This particular sample was taken from a fixed location in the North Sea by researchers from the University of Newcastle. Here, the time delays of the significant multipath reflections are relatively stable but their magnitudes vary significantly. This can be explained in case of similar overlapping in time multipaths where even a minute difference in propagation time can lead to significant constructive or destructive interference patterns.

4. MULTIPATH MODELING

A very simple modeling of multipath can be done by the system shown in Figure 6 together with the impulse response of the system. The multipath is generated by a feedback loop with alternation sign to represent surface and bottom reflections. The bandpass filter represents transducer characteristics as in Figure 1. Although this model does not represent the actual multipath channel, it can be useful for testing the robustness of various modulation schemes.

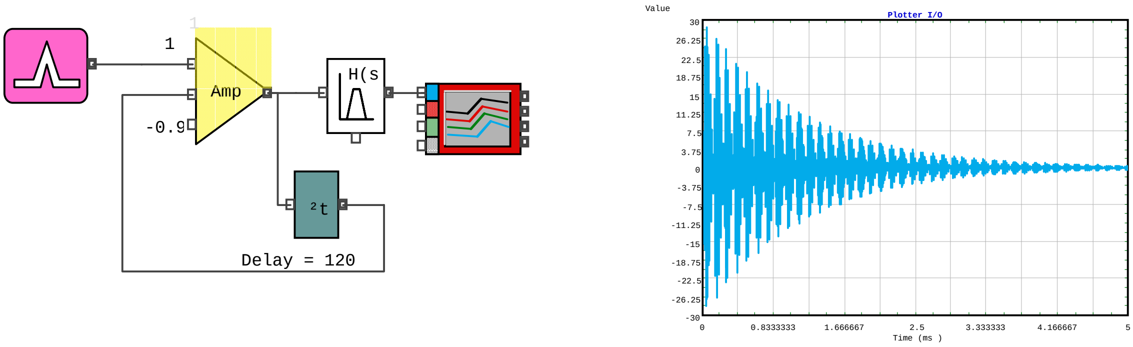


Fig. 6. Multipath modeling

5. ANALOGUE MODULATION SCHEMES

The possible modes of analog modulation of a high frequency carrier include:

- Pulse Position Modulation (PPM);
- Amplitude Modulation (AM);
- SSB Modulation (form of AM);
- Frequency Modulation (FM);
- Phase Modulation (PM).

However, all these schemes suffer from multipath. For instance, applying an AM signal (left graph in Figure 7) to the channel model from Figure 5 results in a distorted received signal (right graph in Figure 7).

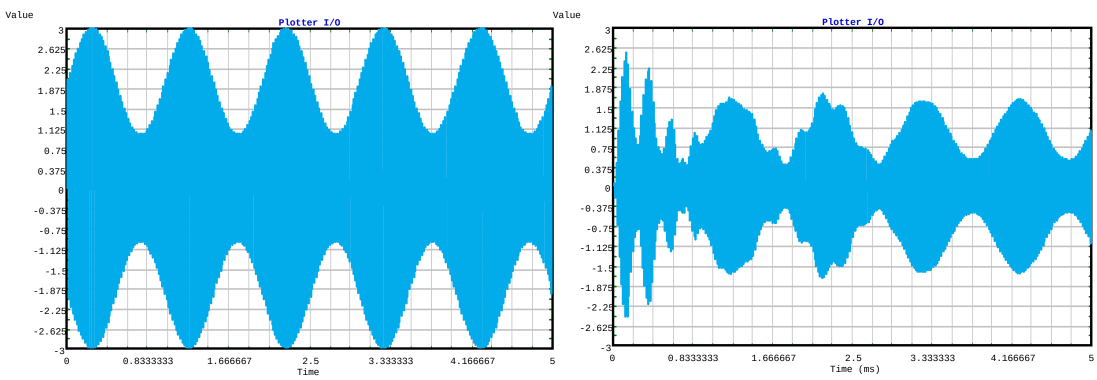


Fig. 7. AM signal in multipath channel

In spite of its drawbacks, analog modulation is typically used for voice transmission. For example, the Model 5400 Underwater Telephone is a compact, high-power underwater telephone for single sideband (SSB) voice operation. The underwater telephone's primary application is communication between any two points in the same body of water at ranges up to 20,000 meters.

Features include:

Synthesized Transceiver, 5-45 kHz
Selectable USB/LSB modulation
Transponder/Interrogator /Pinger /Echo Sounder Mode.

6. FIGHTING THE MULTI-PATH

Narrow-beam acoustic arrays or steerable arrays can be used to direct a transmitted beam in a desired direction and therefore to reduce multipath arriving from other directions. This can be accomplished by acoustic arrays with variable delays in each element of the array. An example of such linear array is shown in Figure 8.

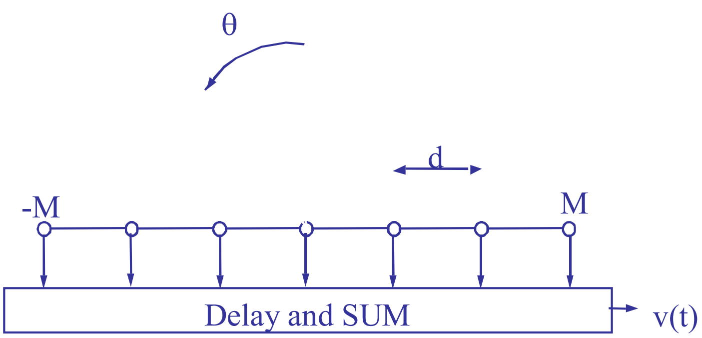


Fig. 8. Steerable array

Such an array can produce a multitude of beams as shown in Figure 9, depending on the delays introduced.

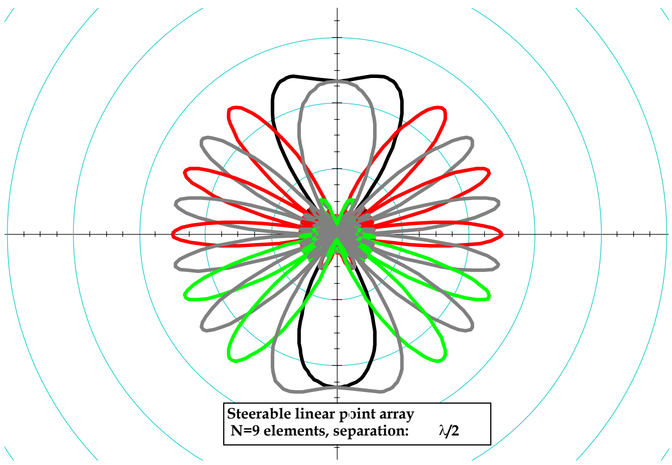


Fig. 9. Steerable beams

7. DIGITAL TRANSMISSIONS – NON-COHERENT MODULATION

Digital acoustic transmission underwater is currently an active research area aimed to achieve reliable, high rate transmissions. Digital techniques allow adaptive equalization to mitigate multipath effects. The purpose of equalization is twofold:

- to produce the desired time domain or frequency domain response of the channel;
- to track changes of the channel in time so that the desired responses are maintained.

The digital modulation used is similar to analog but with only finite levels of information transmitted. M-ary Frequency Shift Keying (MFSK) is an example of such a modulation. Demodulation does not require the recovery of the phase of the carrier. For this reason, such a modulation is called non-coherent. An example of a system using MFSK is the Benthos ATM875/871 Acoustic Telemetry System with the following specifications provided by the manufacturer:

ATM871 Surface Controller
Frequency Band 9-14 kHz (LF), 15-20kHz (MF), 25-30kHz (HF)
Data Modulation 1 of 4 MFSK & Hadamard MFSK
Baud rate 100-2400 bits/s with 1 of 4 MFSK
100-1200 bits/s with Hadamard MFSK
Data Frame Period 25ms
Transducers AT408 Omni, AT409 Line array, AT421 Directional
Dimensions 28 x 36 x 17 cm
Weight 5kg.
ATM875 Underwater Modem
Housing Construction Hard Coat Anodized Aluminum
Operating Frequency 9-14kHz (LF), 15-20kHz (MF), 25-30kHz (HF)
Transducer radiation Pattern Omni, Line array, Directional available
Dimensions 9 cm diameter x 78 cm.
Other non-coherent systems are summarized in Table 2.

Tab. 2. Selected Incoherent Communication Systems

Principal Investigator	Data Rate (bps)	Bandwidth (Hz)	Bandwidth Efficiency (bps/Hz)	Range (km)	Prob. of Errors	Comments on Channel
Morgera(1980)	0.5	50	0.01	N/a	n/a	Simulation
Garrod (1981)	40	n/a	n/a	4	$<10^{-2}$	Shallow
Catipovic(1984)	1200	5000	0.24	3	$\sim10^{-2}$	Shallow
Jarvis(1984)	< 2.3	6000	<3.8 x 10-4	2	n/a	Deep
Coates (1988)	75	1500	0.05	5	$\sim10^{-3}$	Deep
Hill (1988)	360	5500	0.07	6	n/a	Deep
Freitag (1990)	2500	20000	0.13	3.7	$\sim10^{-4}$	Deep
Freitag (1991)	600	5000	0.12	2.9	10^{-3}	Deep
Mackelburg (1991)	1250	10000	0.13	2	n/a	Deep
Scussel (1997)	2500	5120	0.47	10	n/a	Simulation

8. DIGITAL TRANSMISSIONS – COHERENT MODULATION

M-ary Phase Shift Keying (M-PSK) modulation is a coherent modulation requiring carrier recovery at the receiving end. It allows for better bandwidth utilization at the cost of a more complex receiver. Until recently, it was believed that an efficient coherent transmission scheme such as phase modulation was not possible in acoustic underwater channels. The possibility of such transmission was, however, demonstrated using Differential Phase Shift Keying (DPSK) with an adaptive equalizer or, in some cases, even without it. We will present this efficient technique in some detail. The block diagram of a 4-PSK system is shown in Figure 10.

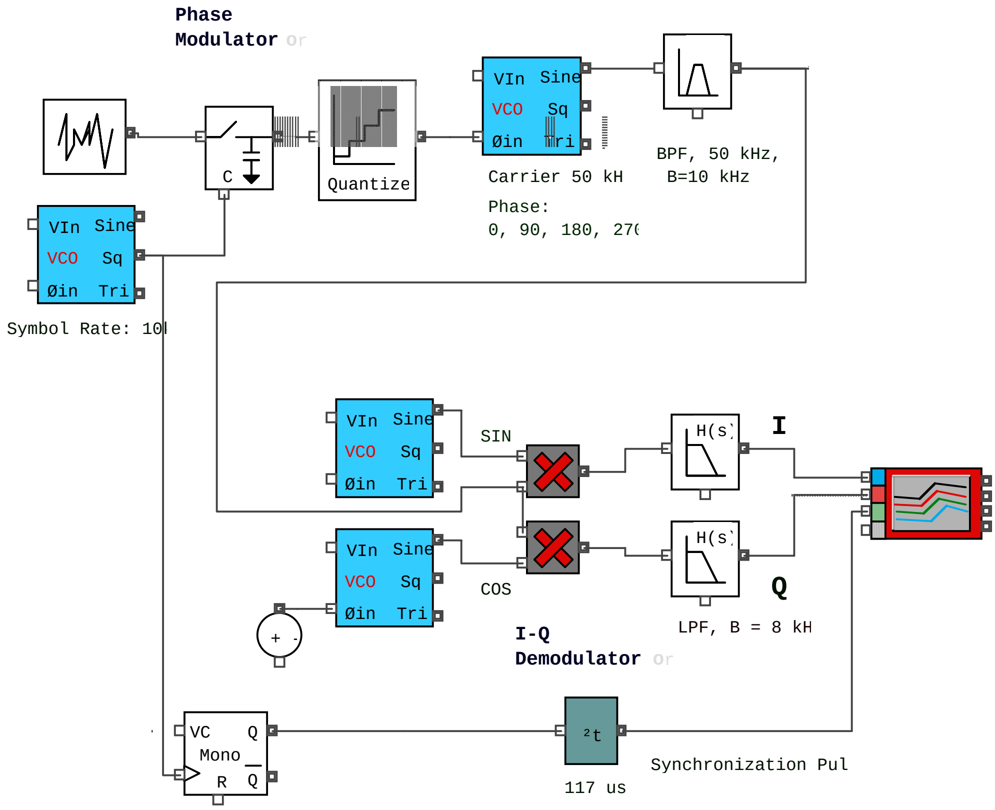


Fig. 10. Block diagram of a 4-PSK system

The symbol generator generates randomly four levels, each representing two bits of information, at the rate of 10 ksymbols/s. This translates to an information rate of 20 kbits/s. The phase of the 50 kHz carrier is modulated by these four levels to four phase values, namely: 0^o, 90^o, 180^o and 270^o. For duration of each signaling element, there are five cycles of the carrier. The phase modulated signal is band-pass filtered by a channel filter at a central frequency of 50 kHz and a bandwidth 10 kHz as described earlier. The relevant waveforms are shown in Figure 11.

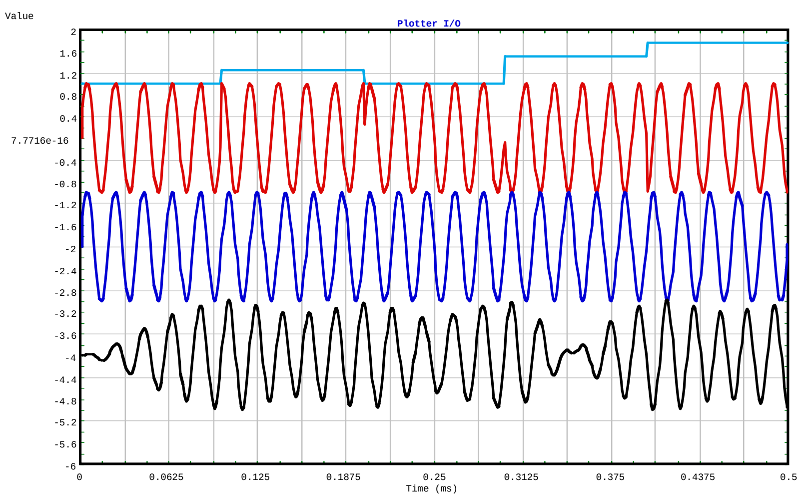


Fig. 11. Modulating and modulated signals

In Figure 11 the traces from the top are:

Trace 1 - Four level phase modulating signal, randomly generated;

Trace 2 - Phase modulated carrier;
Trace 3 - Unmodulated carrier;
Trace 4 - Modulated carrier band-limited by BPF.

The received signal is demodulated by in-phase (I) and in-quadrature (Q) components of the I-Q Demodulator as shown in Figure 10. The demodulator uses perfectly synchronized local SIN and COS oscillators in synch with the oscillator at the modulator. Two identical post-detection low-pass, 5-th order, Butterworth filters (LPF) have a bandwidth of 8 kHz each. The I(t) and Q(t) components represent a time-varying envelope E(t) > 0 and phase φ(t) of the transmitted BP signal. Using complex number notation this can be conveniently written as a complex baseband time-varying signal:

$$\underline{s(t)} = I(t) + jQ(t) = E(t)\exp(-j\varphi(t))$$

that describes the trajectory of the point P[I(t),Q(t)] in time and also shows both the instantaneous phase and the envelope of the transmitted signal. This can be used to determine transmitted phases at suitable sampling instances. This timing information is derived in the block diagram of Figure 10 using a 10 kHz symbol generator. The synchronization pulse for the sampler must be suitably delayed (by 65 μs in this case) to account for the delays introduced by both LPF filters. The waveforms I(t) and Q(t) together with the synch pulse are shown in Figure 12.

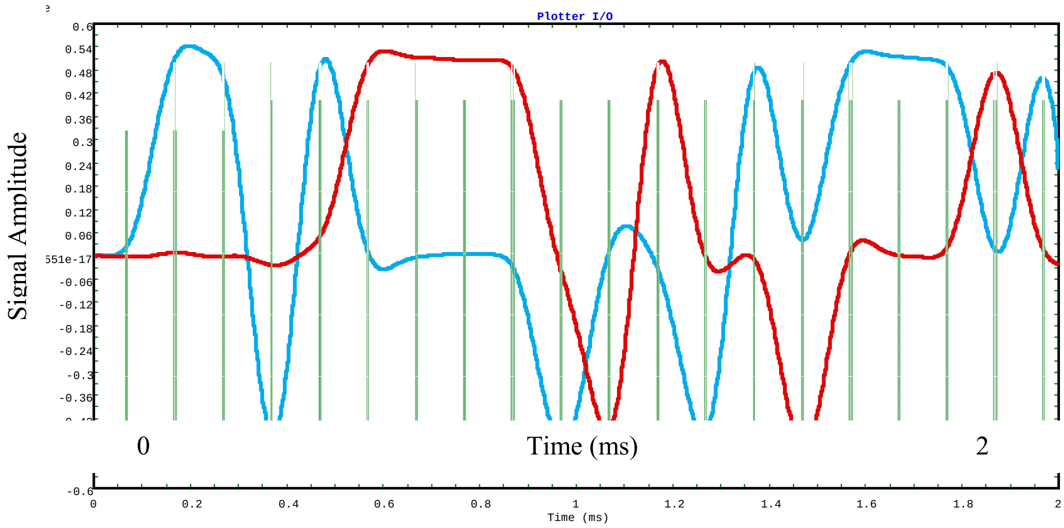
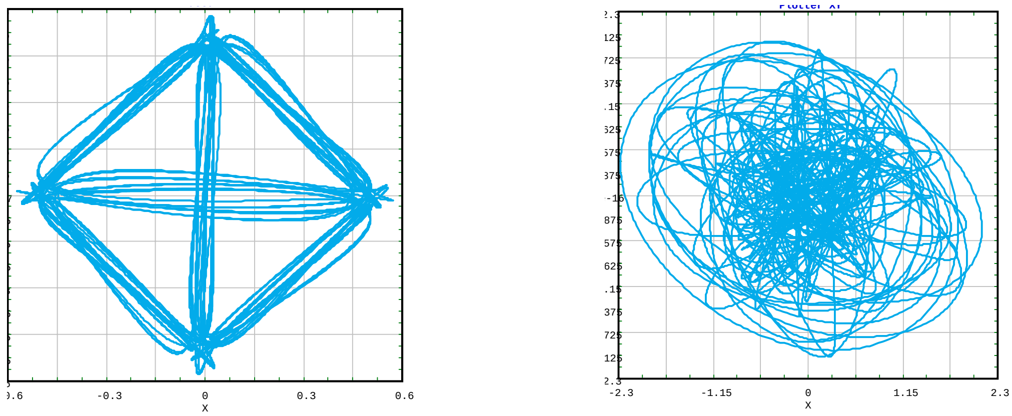


Fig. 12. In-Phase and In-Quadrature components

We can see that with the proper sampling instances, the phase detector can correctly reconstruct the transmitted phases. The phase trajectory can be obtained by plotting parametrically I(t) and Q(t), as shown in Figure 13a. We can identify the four distinct positions of the phase and therefore we have a possibility of the successful demodulation of such a signal. Introduction of the multipath channel destroys those distinct positions, as shown in Figure 13b, and makes it impossible to demodulate the signal.



(a) No multipath (b) with multipath

Fig. 13. Phase trajectories

To restore the distinct phase pattern for a given multipath, we have to lower the signaling rate or use an equalizer or both. The carrier and block synchronization are separate issues that must be implemented in the communication system. An example of a coherent system is M-PSK acoustic modem designed and manufactured by the University of Newcastle upon Tyne, Department of Electrical and Electronic Engineering with the following specifications:

Data Rate:	9600-19200bits/s half duplex
Frequency Band:	8-15kHz.
Transducer options:	Omni-directional or conical beam-patterns Adaptive beam-forming array for horizontal reception
Maximum Range:	3km horizontal or vertical
Bit Error Rate:	Typically $<10^{-5}$ with Reed Solomon error correction coding.
Multi-path Rejection:	Up to 10ms for single transducer systems, much greater with adaptive beamforming array
Transmitting Power Level:	Programmable up to 184dB re 1μPa @ 1m
Power Consumption:	Transmitting: 50W (full power); Receiving: 3W

Other coherent systems (D-PSK) are given in Table 3.

Tab. 3. Selected DPSK Communication Systems

Principal Investigator	Data Rate (bps)	Bandwidth/ Carrier (kHz)	Bandwidth Efficiency (bps/Hz)	Range (km)	Prob. of Errors	Comments on Channel
Mackelburg (1981)	4800	8/14	0.6	4.8	10^{-6}	Deep
Olsens (1985)	2000	2/10	1.0	6.0	$< 10^{-3}$	Deep
Mackelburg (1991)	4800	6/11	0.80	10.0	na	Simulated
Howe (1992)	1600	10/50	0.16	0.1	$< 10^{-3}$	Shallow
Fisher (1992)	625	10/na	0.06	na	na	na
Suzuli (1992)	16000	8/20	2.0	6.5	10^{-4}	Deep
Jones (1997)	20000	10/50	2.0	1.0	10^{-2}	Deep

System performance has greatly improved over the years. Table 4 shows the performance limits in 1990 compared to those of 1980.

Tab. 4. Performance limits

	1980	1990
Range x Transmission rate (km x kbit)	0.5	40 shallow 1000 deep

ACKNOWLEDGEMENTS

I wish to congratulate the dedicated people from the Technical University of Gdansk and the Naval University in Gdynia on the occasion of their XXIth Symposium. I have had the pleasure of attending the majority of these Symposia. It is the very special atmosphere of these Symposia that make for lasting memories.

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